

Element abundances in X-ray emitting plasmas in stars

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Abstract Studies of element abundances in stars are of fundamental interest for their impact in a wide astrophysical context, from our understanding of galactic chemistry and its evolution, to their effect on models of stellar interiors, to the influence of the composition of material in young stellar environments on the planet formation process. We review recent results of studies of abundance properties of X-ray emitting plasmas in stars, ranging from the corona of the Sun and other solar-like stars, to pre-main sequence low-mass stars, and to early-type stars. We discuss the status of our understanding of abundance patterns in stellar X-ray plasmas, and recent advances made possible by accurate diagnostics now accessible thanks to the high resolution X-ray spectroscopy with *Chandra* and *XMM-Newton*.

Keywords Element abundances · X-rays · spectroscopy · stars · X-ray activity

1 Introduction

The determination of the chemical composition of plasmas is of fundamental importance in very different areas of astrophysics. The element abundances in stellar atmospheres have significant impact on the enrichment of the interstellar medium, the evolution of stellar galactic populations, star formation processes, and the structure of stellar interiors.

The solar chemical composition provides the standard reference for the elemental abundances studies of other astronomical objects (see review by Asplund et al. 2009). However, the composition of solar plasmas is not uniform, and in the outer atmosphere is not constant. Evidence for abundance anomalies in the solar corona with respect to the solar photospheric composition arose from early spectroscopic studies of the solar upper atmosphere. Indeed, the solar corona possesses a chemical composition that is

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similar to that of the solar wind and solar energetic particles, and at variance with the underlying photosphere (see reviews by Meyer 1985; Feldman 1992). These abundance anomalies, which will be briefly reviewed in §2.1, reflect the effect of still unknown physical mechanisms of chemical fractionation in the process of mass transport into the corona.

X-ray spectra of other stars provide us with a means to investigate whether, similarly to the Sun, the chemical composition of the stellar outer atmospheres is different from their underlying photospheric mixture. Furthermore, stellar studies allow us to study the fractionation processes as a function of a wide range of stellar parameters, not accessible from solar studies alone. In this paper, we review the current understanding of the chemical composition of the X-ray emitting plasma in stars, as derived from stellar observations in the EUV and X-ray bands during the past two decades, focusing on recent results from high-resolution X-ray spectroscopy. X-ray observations at high spectral resolution now available with *Chandra* and *XMM-Newton* allow us to better disentangle the temperature and abundance effects on the stellar X-ray emission, and represent a significant advance in building a robust scenario for the abundance properties of stellar outer atmospheres.

In §2 we present a review of abundances studies for the solar corona (§2.1) and the coronae of other stars (§2.2). A short discussion of some theoretical studies attempting the modeling of these observed features is included in §2.3. In §3 an overview of abundance studies in X-ray spectra of early-type stars is presented, and finally in §4 we review studies of abundances in pre-main sequence low-mass stars and the possible insights they offer into the physical processes producing X-rays in these young stars.

2 Abundance Patterns and Anomalies in Stellar Coronae

2.1 Solar Abundances

Spectroscopic studies of the solar corona indicate that its hot plasma is subject to chemical fractionation processes in which element abundances can be significantly modified with respect to the photospheric mixture. The abundance anomalies in the solar coronal plasma appear to be a function of the element’s first ionization potential (FIP), with low FIP elements (< 10 eV) found to be enhanced in the corona typically by a factor $\sim 3 - 4$, and high FIP elements ($\gtrsim 10$ eV) having coronal abundances close to their photospheric values (see *left panel* of Fig. 1, and reviews by Meyer 1985; Feldman 1992; see also Sylwester et al. 2010 for recent results on the very low FIP, 4.34 eV, element, K). There is no evidence supporting a mass dependence of the abundance variations (Feldman 1992).

Detailed studies of the chemical composition of solar plasmas have shown that this “FIP effect” varies in different types of solar features – with, e.g., coronal holes, fast solar wind, and newly emerged active regions showing abundances close to photospheric –, from structure to structure, and in time, as shown for instance by Widing and Feldman (2001) for active regions during their evolution (see *right panel* of Figure 1).

Element abundances for the Sun as a star, i.e. from full-disk integrated measurements, are surprisingly scarce (see Laming et al. 1995, and references therein), and it is therefore challenging to estimate the abundances of integrated solar disk spectra from findings concerning specific solar features. Laming et al. (1995), reanalyzing full-disk quiet Sun spectra from Malinovsky and Heroux (1973), recovered the ‘coronal’ FIP

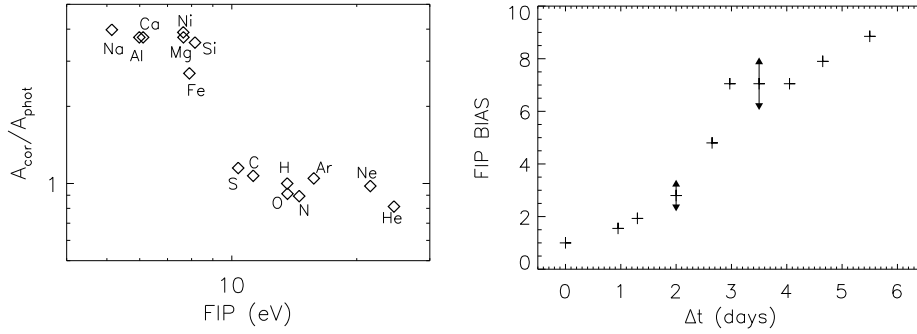


Fig. 1 *Left:* Ratio of coronal (Feldman 1992) vs. photospheric (Anders and Grevesse 1989) abundances for the Sun. Elements with high first ionization potential (FIP), > 10 eV, appear to have coronal abundances close to their photospheric values, while elements with $\text{FIP} \leq 10$ eV are more abundant in corona, typically by a factor $\sim 3 - 4$. *Right:* Evolution of FIP bias (ratio of coronal to photospheric abundances for low FIP elements), in a solar active region over several days as derived from *Skylab* data by Widing and Feldman (2001) (who use Mg/Ne, coronal to photospheric ratio, as a measure of the FIP bias), and showing a steady increase with time of the FIP effect (data from Fig. 3a of Widing and Feldman 2001; error estimates are shown for two measures to indicate typical uncertainties).

effect for the million degree and hotter plasma, while the cooler plasma shows substantially smaller fractionation. They interpret this result as suggestion of a FIP effect as a function of coronal height.

Abundances also appear to vary during flares (see e.g., Sylwester et al. 1984; Feldman and Widing 1990; Phillips et al. 2003; and references in Feldman 1992; Doschek 1990), and in particular there is considerable evidence of Ne-enriched plasma in several flares (see e.g., review by Murphy 2007, and references in Drake and Testa 2005). However, there are also flares where abundances appear to be coronal, i.e. showing the typical FIP effect (e.g., Feldman et al. 2004).

Generally it is not straightforward to determine whether the observed anomalies correspond to an enhancement of low FIP elements in the corona compared to their photospheric abundances, or whether on the contrary the high FIP elements are depleted in the corona. The comparison of the intensity of coronal spectral lines with the underlying continuum emission, which for a solar-like composition arises primarily from H, allows investigation of this issue. Feldman (1992) reviews some results of analyses of solar X-ray spectra: although some studies seem to indicate a depletion of high FIP elements (see also Raymond et al. 1997, 1998), most results appear to point to enrichment of low FIP elements (see also Phillips et al. 2003 and White et al. 2000).

Abundance patterns and their variations in different conditions are important because they provide insights into the physical processes leading to the chemical fractionation of the coronal plasmas, which are likely linked to the elusive heating mechanisms (see §2.3 where we briefly review the status of modeling of the abundance properties in the solar and stellar coronae).

2.2 Stellar Coronae

X-ray emission of low-mass stars presents close similarities with the solar coronal emission and it is indeed assumed that stellar coronae arise from processes analogous to the ones at work on the Sun (see e.g., reviews by Güdel and Nazé 2009; Testa 2010). Early X-ray and EUV studies of late-type stars (based on low to medium resolution *ASCA*, *EUVE*, *BeppoSAX* spectra), however, provided some first indications that abundances in stellar coronae are potentially very different from the solar corona:

- *solar-like FIP effect* for some low to intermediate activity stars, such as α Cen, ϵ Eri, ξ Boo A (e.g., Drake et al. 1997; Laming et al. 1996; Laming and Drake 1999)
- *no FIP effect*: e.g., Procyon (Drake et al. 1995)
- *metal deficiency*, i.e. Fe underabundance in the coronae of active stars (e.g., Schmitt et al. 1996; Singh et al. 1999; Pallavicini et al. 2000)

The robustness of these findings was however difficult to assess because of several intrinsic limitations of the data. For instance, in low-resolution spectra, typically fitted with a few (1-3) isothermal components, emission lines and continuum are entangled and therefore thermal structure and abundances of single elements cannot be tightly constrained. Also in the higher resolution spectra obtained with *EUVE* the determination of element abundances was somewhat hampered by the lack of strong lines of a large number of elements for a wide range of coronal thermal properties (see Drake 2003a, for a discussion). Atomic data applied in global model fitting procedures were also largely untested against high resolution benchmarks, and suspicions of significant deficiencies in terms of completeness in some species were well-founded (e.g., Jordan et al. 1998; Brickhouse et al. 2000).

Another fundamental issue to keep in mind when considering abundance anomalies in stellar coronae, is the fact that stellar photospheric abundances are often unknown, and stellar coronal values are compared with *solar* photospheric abundances. The determination of photospheric abundances is particularly difficult for active stars due to their typical rapid rotation, and subsequent line broadening. This caveat holds true not only for the early results discussed above, and we will discuss it in some more detail in the following.

In the past decade the high spectral resolution provided by the X-ray spectrometers onboard *Chandra* and *XMM-Newton* has provided new, much more accurate, tools for abundance diagnostics. In these spectra, strong, relatively unblended emission lines of several elements (e.g., C, N, O, Ne, Mg, Si, S, Fe) formed over a wide temperature range provide accurate line-based abundance diagnostics.

The first light spectrum of the active RS CVn binary system HR 1099 clearly showed significant abundance anomalies, in particular with evident Fe underabundance and Ne overabundance, and the overall indication of an “inverse” FIP effect (IFIP; Brinkman et al. 2001; see Figure 2), with coronal depletion of low FIP elements and enhancement of high FIP elements.

Studies of increasingly larger samples of high-resolution X-ray spectra of stellar coronae with different characteristics have fleshed out trends of abundance patterns as a function of stellar parameters. In particular, the abundance anomalies appear to change as a function of stellar activity. Audard et al. (2003) had shown the presence of IFIP in several active stars (see also e.g., Huenemoerder et al. 2001; Sanz-Forcada et al. 2003), and hinted at a transition from IFIP to FIP effect for decreasing stellar activity. This effect is evident in large samples of stars when looking at the abundance ratio of

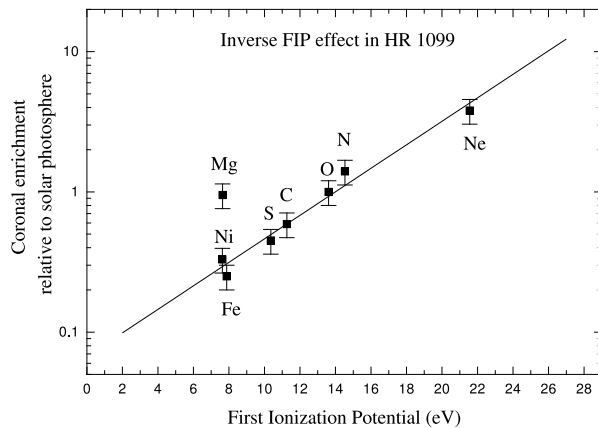


Fig. 2 Element abundances from the *XMM-Newton* high-resolution spectrum of the active binary system HR 1099 (figure from Brinkman et al. 2001). The coronal abundances relative to solar photospheric abundances are plotted. The abundance pattern is opposite to what is typically observed in the solar corona (compare with *left panel* of Figure 1) and it has therefore been dubbed “inverse FIP effect”, by Brinkman et al.

the low-FIP element Fe over the high-FIP element O, as a function of the fractional X-ray to bolometric luminosity (L_X/L_{bol}), which is a measure of the activity level (e.g., García-Alvarez et al. 2009; see Figure 3). The Fe/O observed ratios span a wide range, varying by more than one order of magnitude.

Telleschi et al. (2005) have recently carried out a study of the “Sun in time” analyzing high-resolution X-ray spectra of six solar analogs at different evolutionary stages (and ages from 0.1 to 1.6 Gyr), and studying the evolution of the characteristics of X-ray emission. They found a decline of X-ray activity in all its aspects –X-ray luminosity, flare rate, peak coronal temperature– and also found indication of a corresponding evolution of coronal abundances from an IFIP effect, in the early active stages, to a solar-like FIP effect on short timescales ($\lesssim 300$ Myr, much smaller than the main-sequence lifetime of solar-like stars).

Studies of the Ne/O abundance ratio in stellar coronae, compared to the Sun, have brought about interesting results and some heated debate. As shown for instance in Figure 3 (*right panel*; see also Drake and Testa 2005), the Ne/O ratio is rather constant over a wide range of activity levels¹. This is not surprising as Ne and O both have high FIP, and therefore no strong relative fractionation is expected for these two elements. It is however intriguing that the Ne/O ratio in stellar coronae appears systematically higher (by roughly a factor 2) than the assumed solar photospheric value and typical solar coronal measurements (e.g., Young 2005). This might have important repercussions on an outstanding issue in the modeling of the solar interior. Recently, the use of new realistic 3D time-dependent hydrodynamical models of the solar atmosphere (accounting for the effects of, e.g., convective flows and granulation), together with improvements of atomic data, and relaxation of local thermal equilibrium conditions, has led to a significant downward revision of abundances of several abundant elements, such as C, N, O (Asplund et al. 2005), with respect to the widely used compilation

¹ At least for “normal” coronae; see §4 for a discussion about abundance anomalies in pre-main sequence low-mass stars.

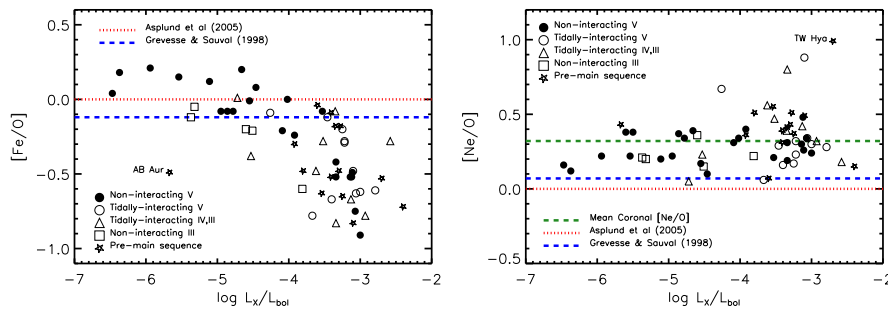


Fig. 3 Coronal Fe/O (*left*) and Ne/O (*right*) abundance ratio relative to the solar photospheric mixture (Asplund et al. 2005) for a large sample of high resolution X-ray spectra of late-type stars with different activity level, age, multiplicity. The abundance ratios (in the bracket notation indicating the logarithmic scale, compared to the corresponding solar value) are plotted as a function of the fractional X-ray to bolometric luminosity (L_X/L_{bol}), which is a measure of the activity level. Fe/O clearly decreases with stellar activity, while Ne/O appears more constant and generally with values a factor ~ 2 larger than the solar photospheric assumed ratio. Figures from García-Alvarez et al. (2009).

of Grevesse and Sauval (1998). This, in turn, broke the previous agreement between helioseismology data and models of the solar interior (Bahcall et al. 2005), because of the reduction of opacity due to the lower C, N, O abundances. An accurate determination of the Ne abundance is potentially important for this issue, because Ne is an abundant element and it contributes significantly to the opacity in the solar interior. Unfortunately, the Ne abundance cannot be measured in the solar photosphere because of a lack of photospheric lines (due to its high ionization potential). As a result, its abundance needs to be inferred indirectly, and it is typically scaled from measurements of solar corona and solar wind by assuming the same Ne/O ratio. If the higher Ne/O of stellar coronae is assumed to reflect the underlying photospheric abundance, and the lower solar coronal Ne/O (and a few other very low activity stars, Robrade et al. 2008) is explained in terms of depletion of Ne with respect to the photospheric composition as also predicted by some models (Laming 2009, see discussion about models in §2.3), the higher photospheric Ne might provide enough opacity to help resolve the “solar model problem” (Drake and Testa 2005; Antia and Basu 2005). However, it now seems unlikely that neon can provide the full solution (Basu and Antia 2008). Also, recent studies of B-type stars, which have photospheric Ne lines because of their hotter photospheric temperatures with respect to solar-like stars, suggest that for those stars the Ne abundance might be higher than the adopted solar photospheric value but not quite as high as observed in active coronae (see e.g., Cunha et al. 2006; Morel and Butler 2008, and also Przybilla et al. 2008 who find Ne/O values only slightly higher than the solar adopted value; see also Wang and Liu 2008 for studies on PNe).

The scenario depicted above, while likely holding in general terms, can break down significantly when looking at specific cases. One very interesting and puzzling case is presented by the binary system 70 Oph studied by Wood and Linsky (2006): the nearly identical stellar components (age, spectral type, activity level, rotation period) have somewhat different properties of their coronal abundances: one component, 70 Oph A ($\log L_X/L_{bol} \sim -5$), shows a prominent solar-like FIP effect, whereas the other component, 70 Oph B ($\log L_X/L_{bol} \sim -4.5$), is characterized by no evident FIP or maybe

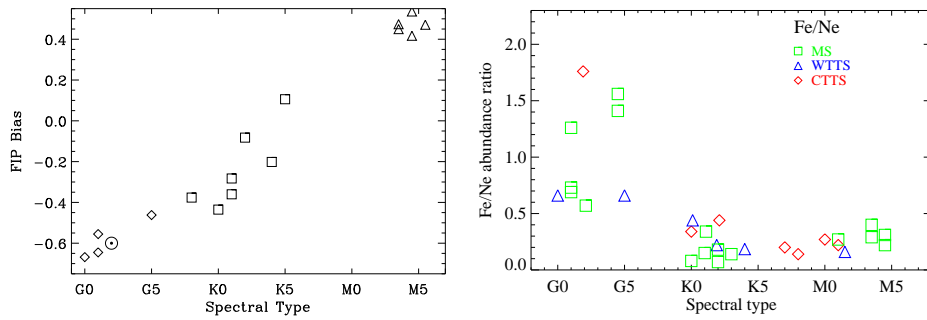


Fig. 4 *Left:* FIP bias, defined by Wood and Linsky (2010) as the average values of coronal vs. photospheric abundances for the high FIP elements, plotted as a function of spectral type for some low to moderate activity stars, with $L_X < 10^{29}$ erg/s (figure from Wood and Linsky 2010). *Right:* Fe/Ne abundance ratio as a function of spectral type for a sample T Tauri stars, and zero-age and active main-sequence stars from high-resolution spectra (figure from Güdel 2007; see also discussion in §4). Red diamonds represent accreting T Tauri stars (CTTS), blue triangles represent weak-line T Tauri stars, while green squares are main sequence X-ray sources.

a even mild IFIP effect. Wood and Linsky (2010) analyze a sample of solar-like stars with low to moderate activity ($L_X < 10^{29}$ erg/s) and find a good correlation of FIP effect with spectral type (see *left panel* of figure 4; we note that for this sample no clear correlation is present between FIP bias and activity level). They find that this correlation considerably weakens when more active stars are included and argue that the rapid stellar rotation in these higher activity stars induces modifications to the fundamental stellar properties to which the fractionation processes might be sensitive. This might be in line with some evidence obtained through the study of young pre-main sequence stars: Telleschi et al. (2007) and Güdel et al. (2007b) have studied T Tauri stars and found some indication of a possible dependence of the FIP effect on the stellar spectral type (see *right panel* of figure 4, and also §4, and Güdel 2007).

Abundance variations in stellar coronae during flares are difficult to establish. High-resolution spectroscopy requires a large number of photons, and with the limited effective areas of the present-day X-ray observatories it is still difficult to carry out detailed time-resolved spectroscopic analysis². Another potential difficulty in deriving abundances reliably from flare spectra is the fact that departures from ionization equilibrium conditions are more likely in flare conditions, whereas spectral modeling usually assumes equilibrium conditions. Previously, analysis of low resolution spectra of a few large flares in active stars provided evidence for an increase in low-FIP element abundances (e.g., Favata and Schmitt 1999; Güdel et al. 1999, for these spectra, Fe often has the better constrained abundance, and uncertainties on derived abundances are generally large). The studies carried out so far on high-resolution spectra suggest in most cases that during flares the abundance anomalies get milder, i.e., abundances appear to get closer to photospheric values during the flare, no matter whether the “quiescent” spectrum is characterized by the FIP or IFIP effect (Güdel et al. 2001; Testa et al. 2007; Nordon and Behar 2008). This effect, if confirmed, is consistent with

² The International X-ray Observatory (IXO), in the planning stages for a launch about a decade from now, and with much larger expected effective area, would make this kind of analysis possible for a large number of stars.

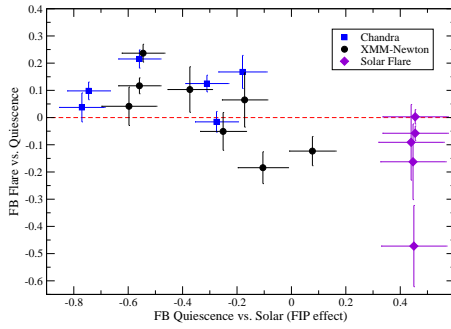


Fig. 5 Abundance variations during stellar flares, as derived from high-resolution spectra. The x-axis indicates the “FIP bias” of the star for the quiescent coronal plasma: on the left are stellar coronae characterized by inverse FIP, and on the right are coronae with FIP effect (and therefore also the solar corona). The y-axis indicates the FIP bias of the flaring plasma vs. the quiescent composition: negative values indicate a relative inverse FIP (e.g., for solar flares a relative enhancement of high-FIP elements and/or depletion of low-FIP elements), and positive values indicate a relative FIP effect in the flare vs. quiescence. The data suggest a pattern of flare abundances being closer to (solar) photospheric mixture, and support a chromospheric evaporation scenario. Figure from Nordon and Behar (2008).

the chromospheric evaporation scenario (e.g., Hirayama 1974; Fisher et al. 1985), and it also supports that the observed abundance trends are a real coronal phenomenon and are not simply reflecting photospheric abundance peculiarities. The sample is however biased towards high-activity stars, and therefore further investigations are needed to confirm this finding. It is also worth noting that there are examples of large flares where no significant abundance changes are observed (e.g., Huenemoerder et al. 2001).

Abundances and stellar evolution — Abundance anomalies of X-ray emitting plasmas in stars can in some cases be used as a probe for stellar evolution, as for instance in the case of Algol. Algol is an eclipsing binary system composed of an early-type main sequence primary (B8 V) and a late-type secondary (G8 III) filling its Roche lobe and losing mass to the primary. The secondary component was initially the more massive star of the system which evolved and lost a significant portion of its initial mass. The X-ray spectrum of Algol shows enhancement of the N/C abundance ratio by an order of magnitude when compared with similar coronal sources (Schmitt and Ness 2002; Drake 2003b), as shown in Figure 6. The anomalous carbon to nitrogen ratio can be explained as a result of the CN-cycle processing in the (now) secondary component (G8 III) evident in atmospheric layers exposed by mass transfer to the primary (Schmitt and Ness 2002; Drake 2003b). By comparing the observed N/C ratio with predictions of evolutionary models, Drake (2003b) estimates that Algol B has lost at least half of its initial mass.

General caveats for studies of element abundances from X-ray spectra:

- Temperature and abundances. The observed spectrum depends on both element abundances and thermal structure, which are often derived simultaneously, either through a global fit of the spectrum (especially for lower resolution spectra) or

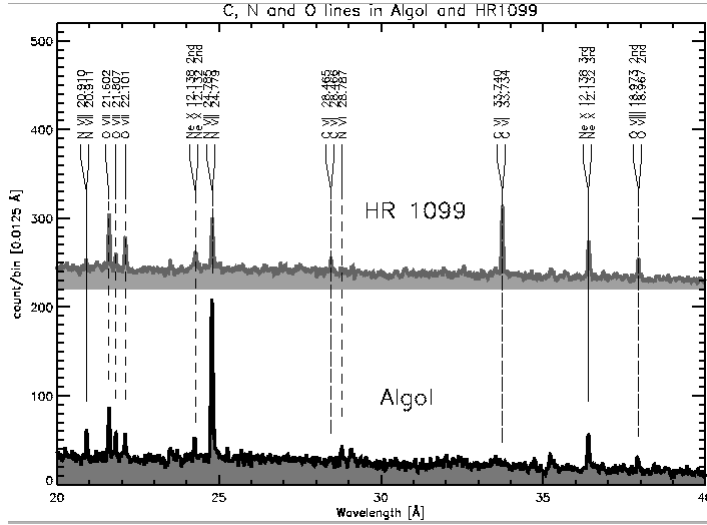


Fig. 6 Comparison of *Chandra* spectra of Algol and HR 1099, in the 2-35 Å range, containing the strong emission lines of C, N, and O (figure from Drake 2003b). Drake (2003b) shows that these two sources have X-ray emission with very similar properties, with the exception of a very different C/N abundance ratio reflecting the effects of CN-cycle processing.

through line-based diagnostics allowing derivation of the plasma emission measure distribution (EMD) and chemical composition. High-resolution *Chandra* and *XMM-Newton* spectra allow us to resolve emission lines and provide us with much more accurate diagnostics to disentangle temperature and abundances. Abundance diagnostics based on temperature independent ratios of combination of strong lines can be developed (see e.g., Drake 2003a; Drake and Testa 2005). This technique has the advantages of providing a diagnostic independent on complex EMD reconstructions, and also, is based on strong lines (H-like, He-like) for which more reliable atomic data exist (and therefore it has intrinsic smaller associated uncertainties). Huenemoerder et al. (2009) compared the results of the two different approaches for the *Chandra* high resolution spectrum of the young binary system θ^1 Ori E (composed of two G III type stars), and find a general good agreement between the temperature independent line ratio method and the full EMD method (see Figure 7).

- High activity bias. High-resolution spectroscopy is biased towards high flux sources, which implies a bias towards high activity levels. Therefore it is often difficult to characterize the abundances patterns and anomalies at the low activity end of the range, closer to the solar activity level.
- Lack of stellar photospheric abundances. As noted above, for most active stars accurate assessments of their photospheric abundances are not available, mainly due to their high rotation rates. For these stars coronal abundances are typically compared to *solar* photospheric abundances, and therefore an apparently significant chemical fractionation might simply be caused by significant departures of the underlying stellar photospheric abundances from those of the Sun. This has been

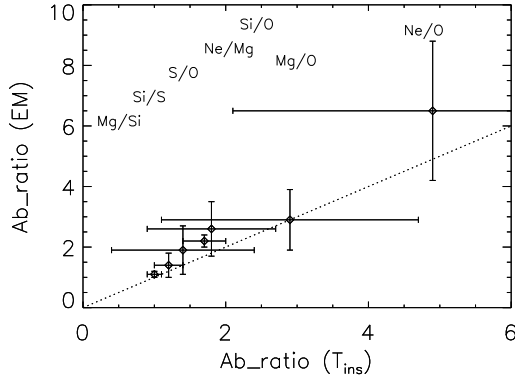


Fig. 7 Comparison of abundance ratios, for θ^1 Ori E, derived with two different methods: (a) based on simultaneous emission measure distribution and abundances analysis, $Ab_{ratio}(EM)$, or (b) based temperature insensitive ratios, $Ab_{ratio}(T_{ins})$. Data from analysis of *Chandra* spectra by Huenemoerder et al. (2009). The large errors for ratios involving oxygen are due to the poor signal in the O VII, VIII lines, which are lying at large wavelength where the instrument sensitivity is lower.

suggested for a few stars by Sanz-Forcada et al. (2004, 2009) but it likely cannot explain the large ranges of fractionation: other cases with accurately determined photospheric abundances still show an inverse FIP effect (Huenemoerder et al. 2001; Sanz-Forcada et al. 2003; Telleschi et al. 2005; García-Alvarez et al. 2005). In order to put the results discussed above on more stable grounds actual stellar photospheric abundances should be derived for a larger sample of active stars for which coronal abundances have been studied.

- Absolute abundances. In general, absolute abundances can prove difficult to constrain, for several reasons such as for instance the above mentioned interdependence of abundances and emission distribution, or the fact that the continuum is often challenging to separate from the pseudo-continuum formed by large numbers of weak lines. Therefore, abundance ratios can usually be determined more accurately than absolute abundances.

We note that most of the above challenges in abundance studies in stellar coronae apply also to the analysis of X-ray emission from massive stars and from young low-mass stars, which are discussed later in §3 and 4.

2.3 Physics of Element Fractionation

The findings discussed so far, clearly demonstrate that the hot plasma in the outer atmosphere of the Sun and several other late-type stars is subject to chemical fractionation, yielding enhancement or depletion of the element abundances up to an order of magnitude and more. Even allowing for uncertainties, for instance due to undetermined stellar photospheric abundances, the observed abundance anomalies are largely described by a FIP or inverse FIP effect. The apparent dependence of the observed fractionation on the element first ionization potential, provides clues as to where in

the stellar atmosphere the fractionation is more likely to happen: in the chromosphere where low FIP elements are ionized and high FIP elements are still mostly neutral.

Several models have been proposed to explain the observed coronal abundance pattern, in particular the solar FIP effect (see e.g., reviews by Henoux 1995; Drake 2003a). Here we briefly discuss some of the physical processes that may be playing a role in the fractionation of elements from the photosphere to the hotter outer layers of the atmosphere of stars, and summarize the most recent viable models; we refer to Henoux (1995), Drake (2003a), and Laming (2004, 2009) for more detailed discussions.

Gravity, temperature gradients, electric and magnetic fields, are all expected to affect the chemical composition of the coronal plasma by acting selectively on the elements depending on either the mass of the ion (e.g., gravitational settling, thermal diffusion), or on the charge of the ion (e.g., frictional drag), or on its charge-to-mass ratio (e.g., ambipolar diffusion). At the same time flows and turbulence effects are expected to work toward mixing the coronal plasma, and can be effective in mitigating or eliminating chemical fractionation. To understand the relative role of each of these effects, it is therefore clearly important to establish the observational constraints in a robust fashion. The extent of the abundance variations, and their variability, or lack thereof, in disk integrated stellar emission can provide us with insights into the properties of the fractionation mechanism(s) and provide tight constraints on the models which need to reproduce the wide range of abundance anomalies as a function of stellar parameters.

Henoux (1995), Drake (2003a), and Laming (2004, 2009) discuss in detail the issues with early models, which were unable to quantitatively explain the wide range of FIP bias values in solar coronal features, and also to reproduce qualitatively both FIP and IFIP effects. Recently Laming (2004, 2009) has modeled the effect on chemical fractionation of ponderomotive forces associated with the propagation of Alfvén waves through the chromosphere. The proposed model is able to reproduce both FIP and IFIP effect, depending mainly on the chromospheric wave energy density, and therefore it also represents a promising step forward in our understanding of both abundance anomalies and possibly coronal heating processes in stellar coronae. To allow for further detailed comparisons, it is important that the inherent assumptions and free parameters are further relaxed or reduced. A interesting prediction naturally arising from Laming’s model concerns the abundances of He and Ne in the outer atmosphere of the Sun. Both elements are predicted to be depleted with respect to their photospheric values. Helium is predicted to be depleted by factors largely consistent with observations of the solar wind (Kasper et al. 2007). The predicted depletion of Ne represents an interesting element in the debate about the solar Ne, which was briefly touched upon in the above.

3 Abundances in X-ray Plasmas in Massive Stars

There are very few detailed studies of abundances of X-ray emitting plasmas in early-type stars. The general properties of the X-ray emission of early-type stars are well explained by a model in which X-rays originate in shocks produced by instabilities in the radiatively driven winds of these massive stars (e.g., Lucy and White 1980; Owocki et al. 1988). However, high-resolution X-ray spectroscopy with *Chandra* and *XMM-Newton* has revealed a somewhat more complex scenario, where at least for some of these massive stars magnetic fields also likely play a significant role (see e.g., Rauw et al. 2008; Güdel and Nazé 2009; Testa 2010, for reviews of recent findings) .

The line formation radius, overall wind properties, and absorption of overlying cool material, need to be modeled in detail in order to reproduce the observed spectra with broad, and often shifted and asymmetric lines. Therefore the analysis of abundances is in general more complex than for X-ray spectra of low-mass stars. It is also worth noting that the chemical composition of the hot photospheres of these stars is generally difficult to constrain (e.g., Bouret et al. 2003; Przybilla et al. 2008; Puls et al. 2008).

With these caveats in mind we proceed and review some recent results of abundance analysis from X-ray spectra of massive stars. Studies of individual stars have shown some interesting insights into the element abundances of the X-ray emitting plasmas. For instance, Favata et al. (2009) have studied X-ray spectra of the Be star β Cep, for which accurate photospheric abundance determinations exist, and found a moderate depletion of most elements in the X-ray emitting plasma compared to the photospheric composition. Kahn et al. (2001) find a high N/C abundance ratio for the O4Ief supergiant ζ Puppis, reflecting CNO processing (see also the discussions about the X-ray abundances of C and N in Algol, at the end of §2.2).

The X-ray spectra of γ Cas, and the “ γ Cas-like” Be star HD 110432, which are hard X-ray sources, provide some of the most interesting results: Fe is found to be significantly underabundant in the hottest spectral component ($\gtrsim 10$ keV) compared to the warm/hot ($\lesssim 3$ keV) component (Smith et al. 2001; Lopes de Oliveira et al. 2007). The authors suggest that a fractionation mechanism might be at work, similar to the process producing the FIP effect in the solar corona.

Zhekov and Palla (2007) analyzed high-resolution X-ray spectra of more than a dozen early-type stars (spectral type O3-B1) and derived an estimate for the element abundances. They find subsolar metallicity, especially for Fe, for which they find values spanning the range $0.2 - 0.6 \text{ Fe}_{\odot}$ (see also Cohen et al. 2010). If confirmed by more realistic modeling of the spectral lines, this result would be very interesting, since it is difficult to imagine that these massive, young stars would have significantly subsolar photospheric metallicity (see age-metallicity relation from, e.g., Holmberg et al. 2007).

4 Abundances in Pre-Main Sequence Low-Mass Stars

Low-mass young stars (T Tauri stars) are strong and variable X-ray sources, and their X-ray emission properties are explained to a large extent by solar-like magnetic activity (see e.g., Preibisch et al. 2005; Güdel et al. 2007a). In T Tauri stars which are still accreting material from their circumstellar disks (classical T Tauri stars, CTTS), however, plasma heated in the accretion shock may produce additional X-ray emission. Classical TTS are on average less X-ray luminous than the non-accreting TTS (by a factor ~ 2), but otherwise their general X-ray emission properties do not differ significantly.

High-resolution X-ray spectroscopy with *Chandra* and *XMM-Newton* allows the determination of much more accurate plasma diagnostics (temperature, density, abundances), and it has provided compelling evidence of peculiar characteristics of the X-ray emission of CTTS that are well described by an accretion related X-ray production mechanism. Specifically, with the exception of the CTTS T Tau (Güdel et al. 2007b), all available high-resolution spectra of CTTS show evidence of unusually high densities for the few million degree plasma, and a soft “excess” revealing an unusually strong cool ($T \sim 2 - 4$ MK) component (Kastner et al. 2002; Stelzer and Schmitt 2004;

Schmitt et al. 2005; Günther et al. 2006; Huenemoerder et al. 2007; Argiroffi et al. 2007; Robrade and Schmitt 2007; Güdel and Telleschi 2007).

Abundance anomalies are also observed in some of these CTTS, although they are not present in all of them. The spectrum of TW Hydrae indicates a strong depletion of Fe and O (with $\text{Fe} \sim 0.2 \text{ Fe}_{\odot}$) and large enhancement of Ne ($\sim 2 \text{ Ne}_{\odot}$) (Kastner et al. 2002; Stelzer and Schmitt 2004). These peculiar abundances, together with the anomalous high density of the strong cool emission, have been interpreted as the effect of metal depletion of grain forming elements (e.g., Fe, O, Si): if dust grains settle in the circumstellar disk midplane while the gas extends up to the disk surface where it can be more efficiently ionized and accreted, then the X-ray emitting accreted plasma would reflect the chemical composition of the gas phase component of the circumstellar material. Other CTTS also show anomalous abundances, and, in particular, an uncommonly high Ne/Fe abundance ratio (e.g., Argiroffi et al. 2005; Robrade and Schmitt 2006). Drake et al. (2005) find that the abundance ratio of Ne/O of TW Hya is anomalously high, by a factor > 2 with respect to other stellar coronae, and also with respect to another much younger CTTS, BP Tau. In agreement with the above scenario, the advanced evolutionary stage of the disk of TW Hya (~ 10 Myr old) implies a high level of depletion of metals locked into grains with respect to volatile Ne. This interpretation is also in agreement with evidence of ongoing coagulation of grains into larger bodies in the disk of TW Hya (Wilner et al. 2005). In the younger BP Tau (~ 0.6 Myr), the disk is expected to be significantly less evolved, and therefore with much more limited dust/gas separation, if any. Drake et al. (2005) therefore advanced the possibility that an anomalously high Ne/O could provide a useful indicator of evolutionary stage of the circumstellar disk in accreting TTS. Further analyses of other high resolution spectra of CTTS have provided ambiguous results: Günther et al. (2006) find for V4046 Sgr, another old (~ 12 Myr) CTTS, Ne/O similar to TW Hya, apparently supporting the scenario depicted above; however, Argiroffi et al. (2007) found a possible counterexample in MP Mus, which despite being likely in a late stage of the pre-main sequence accretion phase (~ 16 Myr) has Ne/O compatible with other coronae (see Figure 8). However, the X-ray spectrum of MP Mus appears to be characterized by an average plasma temperature significantly higher than that of TW Hya and V4046 Sgr, suggesting for MP Mus a larger coronal contribution to the X-ray emission with respect to TW Hya and V4046 Sgr which might have relatively more prominent accretion related X-ray emission. In this scenario, the abundances derived from the spectrum would represent average values of the coronal and accretion shock plasmas weighted by the relative contribution of each component. Even if the data do not rule out the possibility that in MP Mus the lower Ne/O might be due to the more significant coronal contribution to the X-ray emission, Argiroffi et al. (2007) find that this scenario provides a less satisfactory fit to the data, and therefore deem this explanation unlikely.

Scelsi et al. (2007) analyzed a sample of 20 bright TTS (with a signal-to-noise ratio deemed high enough to be able to constrain abundances from medium-resolution spectra) in the Taurus-Auriga star formation region, and find that in this limited sample accreting and non-accreting sources have X-ray emission with very similar temperature and chemical composition. This finding suggests that, in general, accretion related processes are not modifying significantly the chemical composition of the coronae of young active stars.

Studies of abundances from large samples of X-ray spectra of TTS have yielded results sometimes not easily reconciled with the findings for more evolved late-type stars. For instance, Maggio et al. (2007) studied CCD-resolution *Chandra* spectra of

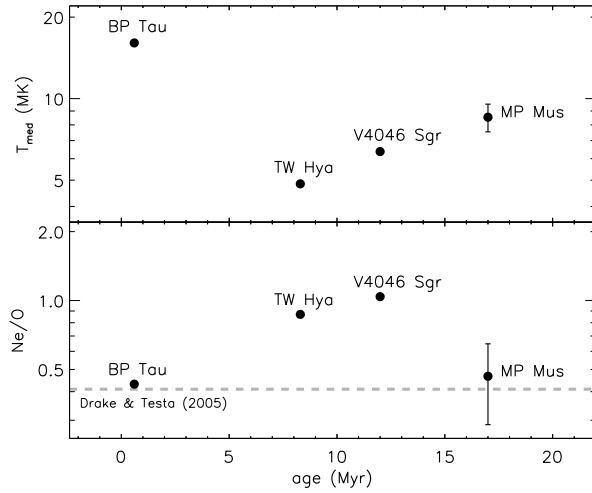


Fig. 8 Average plasma temperature (*top panel*) and Ne/O abundance ratio (*bottom panel*), derived from high-resolution X-ray spectra and plotted vs. age, for a sample of four classical T Tauri stars showing evidence of accretion related processes contributing to their X-ray emission: BP Tau (Robrade and Schmitt 2006), TW Hya (Drake et al. 2005; Robrade and Schmitt 2006), V4046 Sgr (Günther et al. 2006), MP Mus (Argiroffi et al. 2007). Figure from Argiroffi et al. (2007).

146 bright Orion sources and find that for the sample as a whole, and using a set of stellar photospheric abundances or abundances of the Orion Nebula as a reference, only Fe appears significantly fractionated, depleted by a factor 1.5-3. This result might either indicate that the abundances used as the photospheric reference do not represent accurately the photospheric composition of this sample, or it might point instead to an actual absence of a clear IFIP effect at variance with the results discussed in §2.2 for more evolved stars with similar activity levels. This latter case would imply significant differences in the fractionation processes at work in these young stars with respect to their more evolved counterparts. Telleschi et al. (2007) from the high resolution *XMM-Newton* spectra of 9 TTS find that a FIP dependent fractionation effect is present and seems to change as a function of the stellar spectral type. Specifically Ne is overabundant ($\text{Ne}/\text{Fe} \sim 4 - 6$ times solar) in K and M-type stars, while earlier type have higher Fe abundance (see right panel of Figure 4). Stellar mass and gravity do not appear to influence the coronal abundances. Although this result echoes the results found by Wood and Linsky (2010) for solar-like main sequence stars (as discussed in §2.2), the young stars studied by Telleschi et al. (2007) are much more active, with typical luminosities above 10^{30} erg/s, i.e. in the range of activity where the correlation of FIP bias and spectral type found by Wood and Linsky (2010) breaks. In summary, the possible dependence of element fractionation mechanisms on the spectral type and evolutionary phase is an open issue to be addressed through the study of larger samples of stars, both in early evolutionary stages and in main sequence.

5 Conclusions

In this paper we have reviewed recent advances in our understanding of the chemical composition of X-ray emitting plasma in stars brought about in the past decade. In particular, high-resolution X-ray spectroscopy with *Chandra* and *XMM-Newton* has allowed robust determination of the element abundances from X-ray spectra indicating that the abundance anomalies in stellar coronae are real and not an artifact of the modeling of low and medium resolution spectra.

Abundance anomalies in coronae of cool stars are largely described by fractionation processes dependent on the element's first ionization potential, and they appear to be a function of the stellar X-ray activity level. A solar-like FIP effect (abundance enhancement of low-FIP elements in coronal plasma) is typically observed in other low to intermediate activity stars similar to the Sun, whereas high activity stars are characterized by an inverse FIP effect (depletion of low-FIP elements in the corona). These findings, however, heavily rely on the assumption that the often unknown underlying stellar photospheric abundances are similar to the solar photospheric abundances. More photospheric abundance studies are needed in order to uncover the true coronal abundance anomalies in a more reliable way and firmly establish the validity of the apparent trends.

The abundance of neon shows an interesting pattern with active stars showing a Ne/O abundance ratio significantly larger than the Sun and other low activity stars. This might point to a fractionation of Ne in coronal plasma, either depletion in solar-like activity stars or enhancement in active stars, and raises the issue of what the photospheric Ne abundance is in the Sun and in nearby stars.

Studies of flares suggest significant abundance variations compared to quiescent conditions, though the limited quality of the time-resolved spectroscopy achievable at present, and the effects of non-equilibrium, which are difficult to model and constrain, cast some doubts on the robustness of these findings. Improved capabilities for temporally resolved spectral diagnostics are required to be able to confirm these results.

Recent studies also suggest that the chemical fractionation of coronal plasma might depend on the stellar spectral type. This dependence, however, appears to apply only to low to intermediate activity stars, with possibly important consequences in the context of developing a theoretical framework to interpret the abundance anomalies. In fact, this finding can put significant constraints on the models as it might suggest that instead of a unique mechanism of fractionation for all coronae, different processes might be dominant in stars similar to the Sun and in stars with higher activity level.

For massive stars, an accurate knowledge of the abundances of their X-ray emitting plasmas is still lacking. However, recent investigations with high-resolution spectra have produced interesting results, suggesting subsolar Fe abundance for several early-type stars, and a possible temperature dependent solar-like FIP effect in some sources with hard X-ray spectra.

In young low-mass stars the chemical composition of X-ray plasmas typically shows characteristics analogous to more evolved stars with similar activity levels, i.e., an inverse FIP effect, in particular with low Fe abundance and high Ne. Also for pre-main sequence stars more reliable photospheric abundances need to be determined in order to establish the actual extent of these apparent coronal abundance anomalies. The coronal abundances of T Tauri stars do not appear to depend on the presence of ongoing accretion or lack thereof. A few unusually old accreting T Tauri stars show peculiarly high Ne/O abundance ratio in their X-ray emission; this anomalous chemical composi-

tion is suggestive of advanced evolution of the circumstellar disk yielding depletion of grain-forming elements, compared to Ne which is volatile. These abundance peculiarities, however, are not found consistently in other old accreting T Tauri stars therefore questioning the validity of this scenario.

Although the study of the element abundances in stellar X-ray plasmas has recently yielded significant progress, substantial improvements on both the observational constraints and theoretical models are required to begin understanding the physics of chemical fractionation in stars. This process is likely connected to the yet poorly understood mechanism(s) of mass and energy transport to the corona, which are among the most fundamental open issues in astrophysics.

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